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# Pronated Escape System (PRESS)

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# Pronated Escape System (PRESS)

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**Aerodynamic and biomechanic analyses are presented for a fighter seat and escape system. A semi-enclosed seat configuration is described that provides pilot protection for ejections at a dynamic pressure of 2000 psf, well beyond the capability of existing open-seat ejection systems. Increased ejection performance is achieved by taking advantage of a pronated (forward-leaning) seat configuration to increase pilot protection from windstream deceleration forces, and provide stability in the windstream prior to deployment of the drogue chute. These enhancements, in conjunction with the increased pilot g-tolerance during flight (described herein), make the concept of a pronated fighter seat very attractive. A computer model of pressure distribution on panels was used to predict aerodynamic forces and moments. Computer simulation of ejection dynamics was used to predict dynamic stability.**

## Nomenclature

$A_w$ = windstream deceleration of the seat, ft/s²
$C_d$ = drag coefficient
$C_{ll}$ = rolling moment coefficient
$C_{ln}$ = yawing moment coefficient
$C_m$ = pitching moment coefficient
$C_p$ = coefficient of pressure
$D$ = drag, psf
$DR(t)$ = dynamic response, ft/s²
$d$ = equivalent hydraulic diameter of $S$, ft
$g$ = gravitational constant, ft/s²
$h$ = hydrostatic column of blood, cm
$K$ = pressure coefficient
$m$ = mass, slugs
$q$ = dynamic pressure, psf
$S$ = reference seat cross-sectional area, ft²
$s(t)$ = translation component input acting at the critical point along the orthogonal axis of interest, ft
$w_n$ = undamped natural frequency of the dynamic model, rad/s
$\alpha$ = angle of attack, deg
$\beta$ = sideslip angle, deg
$\delta$ = the angle between the panel surface and the freestream vector, deg
$\delta(t)$ = relative distance of the hypothetical model mass due to the accelerative force input, ft
$\theta$ = a particular seat back/front angle, deg
$\phi$ = the value of $\theta$ required to place the eye directly above the aortic valve for a particular seat, deg
$\xi$ = damping coefficient of the dynamic model

## Introduction

AIRCRAFT maneuverability is the key to air combat superiority. Improvement in maneuverability generally means improvement in aircraft turn performance and an associated increase in aircraft acceleration. With the incorporation of more powerful engines, lightweight composite materials, high-lift wings, and other technological advances that allow current fighters to sustain higher g-loads; g-tolerance of the pilot frequently is the limiting factor in utilizing an aircraft to its maximum capability. Since future fighters will be even more maneuverable, there is need for enhancement of pilot g-tolerance.

In addition to greater maneuverability, future fighters are expected to fly for extended period of time at speeds greater than Mach 3 and dynamic pressures of 2000 psf. As average mission speed increases, more high-speed ejections can be expected. The major hazards in high-speed ejections are 1) deceleration forces that may induce spinal and visceral injuries, and 2) increased windblast burn and flailing injuries.

The fighter seat that supports the pilot in a forward-leaning position is particularly suited to improving pilot g-tolerance and increasing the high-speed and dynamic pressure limits on ejection. In this paper, a fighter seat design, which supports the pilot's torso in the pronated position, is described that permits ejection at a dynamic pressure of 2000 psf, while providing g-tolerance capability equivalent to that of a 61 deg reclined seat but with improved visibility.

## Background

Currently, there are two commonly used ejection concepts: encapsulated cockpits and open ejection seats. Encapsulated cockpits eliminate windblast injuries and greatly improve protection against decelerative forces due to their larger mass. However, they impose a large weight penalty on aircraft performance. A single-seat capsule can protect a pilot for ejections up to a dynamic pressure of 2000 psf, but its 800- to 1000-lb weight is not preferred for use in highly maneuverable fighter aircraft.[1]

The current state-of-the-art open ejection seat is the ACES II. It is lightweight (151 lb) and reclined 30 deg in the F-16 for some enhanced pilot g-tolerance.[2] However, at ejections above 1100 psf it does not adequately protect the pilot from spinal and visceral injuries due to decelerative forces, or flailing injuries due to windblast. One proposed seat design that yields significant pilot g-tolerance is the Pelvis and Legs Elevated (PALE) ejection seat.[3] The pilot's upper torso is reclined 65 deg to enhance pilot g-tolerance and, with some difficulty, could be positioned for windblast protection upon ejection. However, this configuration requires excessive cockpit space and limits the pilot's ability to see out of the aircraft.

This paper describes the Prone Escape System (PRESS),[4] which optimizes pilot body position for g-tolerance and the ability to see out of the aircraft, as well as protects him from

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spinal and visceral injuries due to decelerative forces upon ejection. These benefits are realized without large size or weight penalties.

## PRESS Description

The PRESS concept was developed at the Air Force Institute of Technology, Wright Patterson Air Force Base.[4] It was designed for a future fighter aircraft to allow the pilot to tolerate greater $g$-forces and safely eject at dynamic pressures up to 2000 psf. Human factor, biomechanic, aerodynamic, propulsion, and control analyses yielded the PRESS seat as shown in the artist's conception of Fig. 1.

Two major seat components, the chest support and the front cowling, significantly contribute to the advanced performance of PRESS. These are shown in Fig. 2, a perspective sketch of the concept developed during the validation study. The chest support, which is covered with rate-dependant foam to distribute and absorb forces, is canted forward at an angle such that inflight $g$-tolerance and ejection dynamic pressure limits are greatly improved. The front cowling ejects with the seat to provide windblast protection and aid in aerodynamic stabilization.

A face shield stored in the front section extends up during ejection to provide windblast protection for the pilot's head. A chin rest that conforms to the pilot's full face helmet is at the top of the chest support. A seat pan adjusts up and down with respect to the chest support to accommodate any size pilot. A rocket catapult is in the seat back as is a vernier control rocket used for seat pitch control. Ejection rails are located in the seat back to guide the seat and to assist in seat/aircraft separation. The pilot's seat is comparable in size to conventional open ejection seat systems and weighs 315 lb.

## *g*-tolerance

The $g$-tolerance associated with a fighter seat is directly related to the seat-inclination angle $\theta$. The seat angle for a reclined seat is defined as the angle of the seat back measured from the aircraft's $Z$-axis. This angle is negative for PRESS due to the forward-leaning chest support.

$g$-tolerance is defined as the pilot's ability to tolerate accelerative forces and still retain vision and can be quantified by using the hydrostatic theory of blackout.[5] Blackout is the point when the pilot, while experiencing accelerative forces, loses sight due to a lack of blood flow to the eye. This theory of blackout proposes that there is a direct correlation between the hydrostatic column of blood supplying the eye and $g$-tolerance. The hydrostatic column $h$ is the magnitude of the component of the position vector directed from the aortic valve to the eye that is parallel to the aircraft acceleration vector. Figure 3 shows an $h$ vs relaxed $g$-tolerance relationship. Relaxed tolerance was measured without any acceleration protection techniques or equipment used (i.e., anti-$g$ suit, M-1 maneuver, etc.).[5] A smaller $h$ decreases the blood pressure needed to supply blood to the eye, thus increasing the $g$-tolerance of the pilot. Burns has shown a significant improvement in $g$-tolerance by using the reclined seat position.[6,7] These studies show that to reach a significant level of $g$-tolerance, the seat must recline to the 60–80 deg range. Unfortunately, afterward visibility and the forward cockpit display area are very restricted at these large seat angles. A smaller $h$ can also be attained by leaning forward, which is defined as the pronated position.

The method used by Burns was adapted to determine $h$ for both the reclined and pronated positions at different angles. The mean value of the vertical component of the hydrostatic column $h'$ is approximately 34 cm in an upright man. The equation for an approximate vertical hydrostatic column is

$$h = [h'/\cos(\phi)]*\cos(\theta - \phi) \tag{1}$$

$\phi$ is the angle that the eye is forward of a vertical line drawn through the aortic valve and is between 13 and 17 deg for an upright man. The conservative value of 13 deg is used for this study.

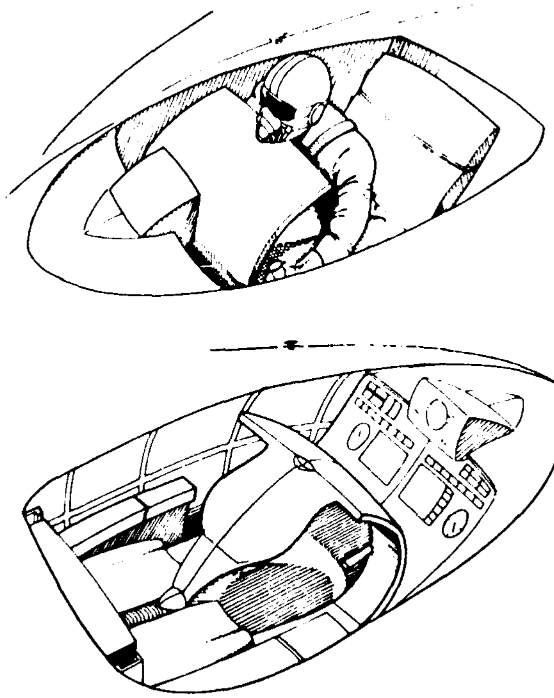


**Fig. 1 PRESS in generic cockpit (artist conception).**

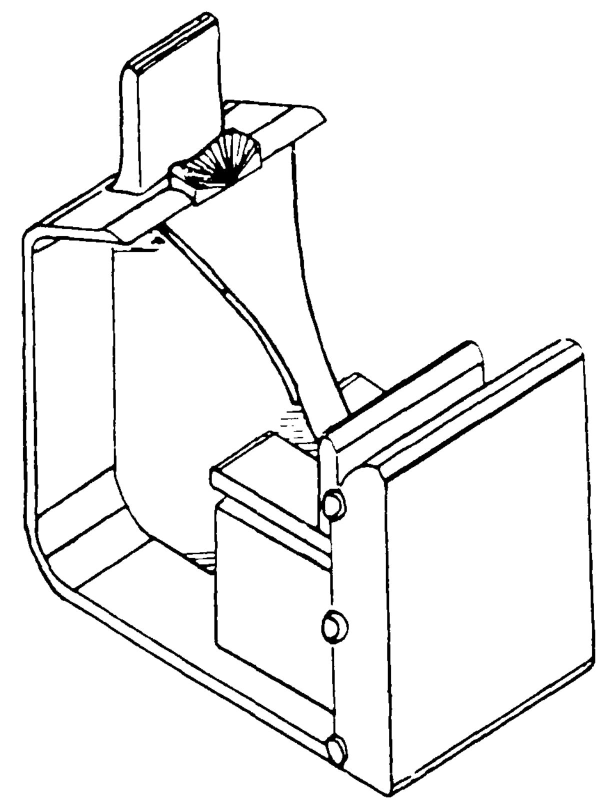


**Fig. 2 PRESS configuration analyzed in the concept validation study.**

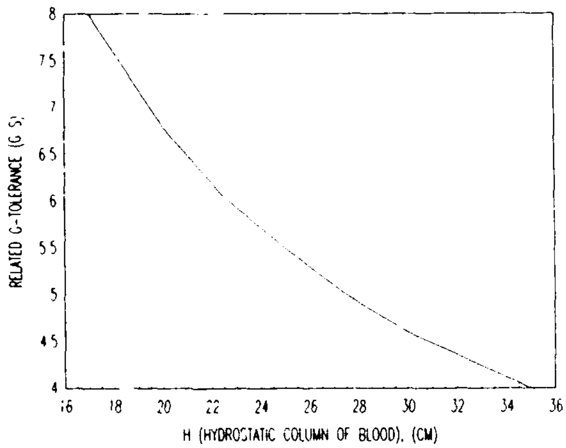



**Fig. 3 Relationship of hydrostatic column of blood ($h$) and relaxed $g$-tolerance**

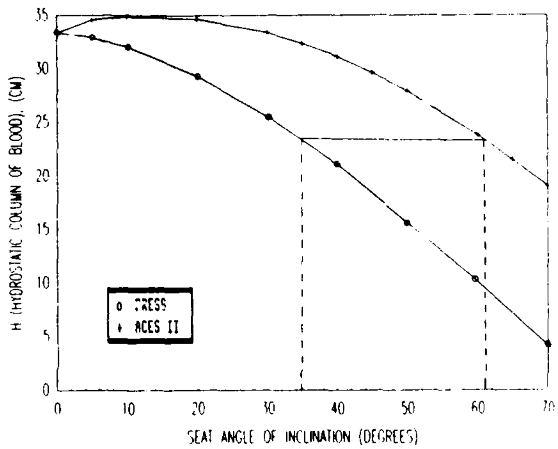



**Fig. 4 Comparison of $h$ values for reclined and PRESS seats at various seat angles.**

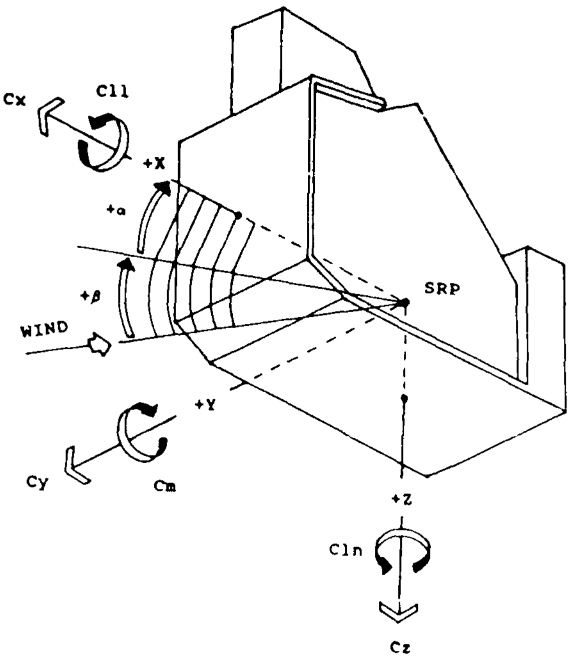



**Fig. 5 SHABP input geometry model with aerocoefficients.**

Since the eye is forward of the aortic valve for an upright or vertical person, leaning forward is a more effective way to decrease $h$. Figure 4 contains a comparison of $h$ values between the Burns reclined seat and a pronated seat based on Eq. (1). There is a significant difference in $h$ between the two seats. For example, the pronated seat at $-35$ deg achieves roughly the same $g$-tolerance as the reclined seat at 61 deg.

Improving $g$-tolerance with a reclined or pronated position degrades visibility. To assess the degradation, visibility was subjectively measured using a full-scale wooden mockup of the pronated seat.[4] Several experienced fighter pilots were asked to identify appropriate seat-inclination angles. The consensus was that angles beyond $-45$ deg were uncomfortable and would hinder the flying capability of the pilot.

A seat angle of $-35$ deg, which is within this qualitatively established visibility limit, was selected for establishing pronated seat feasibility, since its performance could then be readily compared with the PALE reclined system, which hydrostatic theory predicts to have similar $g$-tolerance. Further research is required to quantify the tradeoff in $g$-tolerance and visibility. In so doing, it is recommended that visibility be measured in $g$-loading conditions, since the ability to move the head in the two seating positions is likely to be different.

## Aerodynamic Analysis

Aerodynamic data did not exist for a shape similar to PRESS; therefore, the Mark IV Supersonic-Hypersonic Arbitrary-Body Program (SHABP) was used to compute the data.[8] SHABP is a panel method code based on impact pressure distributions that are converted to aerodynamic forces and moments. Previous work on an ACES II ejection system by Chaing compared the output from SHABP with wind-tunnel data and concluded that the program was an adequate engineering tool for escape system preliminary design and development work.[9]

The PRESS input geometry shown in Fig. 5 is a simple paneled representation of the seat and a 50th percentile pilot. The modified Newtonian method was used for data computation. The pressure of high-speed flow is defined by the equation

$$C_p = K \sin^2(\delta) \tag{2}$$

The value of the pressure coefficient established by Chaing for blunt escape systems $K = 1.4$ was used.[9]

SHABP was run at supersonic conditions for various angles of attack and sideslip. The coefficients are based on reference area $S = 6.19$ ft$^2$ and a reference moment arm $d = 2.84$ ft equal to the equivalent hydraulic diameter of the area.

## Stability Analysis

The moment coefficient data for the runs are represented graphically in Fig. 6. The pitch trim angle is approximately 50 deg as determined from the pitching moment coefficient $C_m$ vs $\alpha$ curve. The slope of the curve indicates that the seat/pilot configuration has static longitudinal stability ($\partial C_m/\partial\alpha$) for 5 deg $\leq \alpha \leq$ 85 deg and neutral stability for $-30$ deg $\leq \alpha \leq$ 5 deg and 85 deg $\leq \alpha \leq$ 95 deg. The seat has static directional stability ($+\partial C_{ln}/\partial\beta$) for 0 deg $\leq \beta \leq$ 7 deg and neutral stability for 7 deg $\leq \beta \leq$ 30 deg. Because of the symmetry, this result also applies for negative $\beta$. The seat possesses neutral static lateral stability for 0 deg $\leq \beta \leq$ 12 deg and is laterally stable ($-\partial C_{ll}/\partial\beta$) for $\beta$ greater than 12 deg. Symmetry also holds here.

PRESS is statically stable in pitch and yaw and neutrally stable in roll in the vicinity of the ejection attitude, and has a significant range of pitch stability that can be used to advantage when positioning the pilot for increased deceleration tolerance. This is an important characteristic of the PRESS seat. At dynamic pressures above 950 psf, stability is essential,

since a drogue chute cannot be deployed without exceeding the acceleration limits of the pilot. Also, a stable ejection seat greatly simplifies the control system required.

### Acceleration Exposure Limits

Brinkley has related the acceleration exposure limits of the human body to the probability of injury, termed injury risk levels.[10,11] His method uses a mass-spring-damper system to model the whole-body response to short-duration accelerations. The equation that describes the dynamic model response along each othogonal body axis is

$$\ddot{s}(t) = \ddot{\delta}(t) + 2\xi w_n \dot{\delta}(t) + (w_n)^2\delta(t) \tag{3}$$

and the dynamic response is

$$DR(t) = (w_n)^2\delta(t)/g \tag{4}$$

The body's tolerance to short-duration acceleration depends on the magnitude, direction, and sense of the acceleration. Acceleration limits are generally stated for senses along three orthogonal body axes. By convention, a left-handed body axis coordinate system defines the accelerations acting on the pilot. A $+Z$ acceleration acts from the feet to the head and a $+X$ acceleration acts from the pilot's back to his front (i.e., eyes out). The $Y$-axis is positive from the pilot's left to right.

For multiaxial accelerations, the surface of an ellipsoidal envelope defines the three-dimensional human acceleration exposure limits. The axes of the ellipsoid represent the axial human exposure limits for a given injury risk level. A given acceleration exceeds an injury risk level if its multiaxial components, when substituted into Eq. (5), cause the value to exceed 1.0.

$$\left[\frac{DRx(t)^2}{DRx_L^2} + \frac{DRy(t)^2}{DRy_L^2} + \frac{DRz(t)^2}{DRz_L^2}\right] \leq 1.0 \tag{5}$$

The subscript $L$ refers to the limiting value of the computed dynamic response for the assigned injury risk level along the axis of interest. Table 1 presents the risk levels and corresponding acceleration exposure limits for each direction and axis of the body. The low-, moderate-, and high-risk levels are approximate 0.5, 5.0 and 50.0% probabilities of injury. The low-risk level corresponds to acceleration conditions routinely used in acceleration test with volunteers with no incident of major injury. The moderate-risk level nearly corresponds to the acceleration limits specified in the general design specification for U.S. Air Force upward ejection seats, MIL-S-9479B, but is more liberal for acceleration pulses with durations less than 0.03 s.[12] The high-risk level is the level of acceleration where major injuries and potentially serious conditions, such as cardiovascular shock or spinal fractures, are known or believed to occur. For the $+Z$-axis, these risk levels correspond to the 0.5, 5.0, and 50.0% probability of spinal injury.

The following assumptions govern the ejection seat after separation from the aircraft:

**Table 1 Acceleration exposure limits**

| | $DRx_l$ | | $DRy_l$ | | $DRz_l$ | |
|---|---|---|---|---|---|---|
| | $DR_x > 0$ | $DR_x < 0$ | $DR_y > 0$ | $DR_y < 0$ | $DR_z > 0$ | $DR_z < 0$ |
| Low risk | 35 | 28 | 14 | 14 | 15.2 | 9 |
| Moderate risk | 40 | 35 | 17 | 17 | 18 | 12 |
| High risk | 46 | 46 | 22 | 22 | 22.8 | 15 |

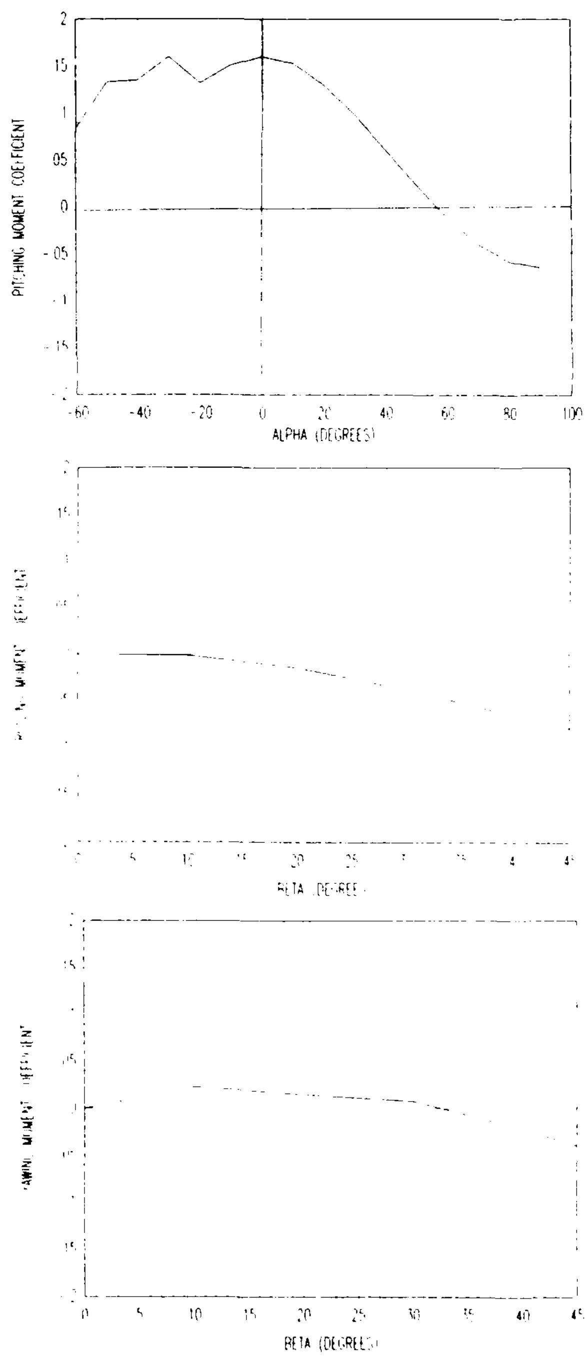



**Fig. 6 Supersonic aerodynamic moments about the center of gravity for PRESS.**

1) After separation from the catapult guide rails, the seat experiences only variations around the pitch axis. The simulation results (discussed later) support this assumption. The seat's angle of attack varies as it rotates to its stable pitch angle. Therefore, the pilot only experiences accelerations in the body's $X$-$Z$ plane. Accelerations in the $\pm Y$-axis are negligible.

2) The seat restraints hold the pilot's torso during the ejection sequence.

3) The seat can be modeled at point mass body.

4) The acceleration exposure limits of Table 1, which orignate from experimental data and observations of ejections from conventional seats, also apply to an ejection seat with a seat front.

Note that Eq. (5) is based on dynamic response variables. For the purpose of this analysis, these must be related to static decelerative forces. It was found in PRESS simulations that the dynamic response can be approximated by the accelerative force in each direction at any instant of time.[4] Then, for the pilot's torso inclined at an angle from the vertical, the following multiaxial acceleration exposure limit equation applies:

$$\left\{\frac{[A_w \cos(\alpha+\theta)]^2}{DRx_l^{\,2}}+\frac{[A_w \sin(\alpha+\theta)]^2}{DRz_l^{\,2}}\right\}^{1/2} \le 1.0 \qquad (6)$$

Solving for $A_w$, the equation for the acceleration limit of the pilot becomes

$$A_w = 1.0/\left\{\frac{[\cos(\alpha+\theta)]^2}{DRx_l^{\,2}}+\frac{[\sin(\alpha+\theta)]^2}{DRz_l^{\,2}}\right\}^{1/2} \qquad (7)$$

The acceleration limits of PRESS and ACES II that result from evaluation of Eq. (7) at a moderate injury risk level are plotted in Fig. 7 for angles of attack between 0 and 90 deg. The maximum acceleration in each case occurs when the spine is perpendicular to the windstream and is equal to the $DRx_L$ limit for $DRx < 0$ of Table 1. In the case of ACES II, this occurs at an angle of attack of $-30$ deg, since the pilot is realigned 30 deg from upright. For PRESS, this limit occurs at an angle of attack of 35 deg, the negative of the seat front angle. This variation in angle of attack at which maximum tolerance occurs is used as an advantage for the PRESS design, as described in the next section.

### Optimizing Windstream Deceleration Limits

Acceleration limits associated with windblast deceleration are normally expressed as equivalent dynamic pressure limits. Applying Newton's equation to the limiting drag is expressed as

$$D = mgA_w \qquad (8)$$

The dynamic pressure determines the drag force

$$D = C_d S q \qquad (9)$$

Equating these two expressions and solving for the dynamic pressure limit in terms of the deceleration due to the windstream

$$q = gmA_w / C_d S \qquad (10)$$

The dynamic pressure limit is proportional to the product of the seat mass and the acceleration exposure limit and inversely proportional to the product of the drag coefficient and frontal reference area, i.e., inversely proportional to $C_dS$. $C_d$ is plotted in Fig. 8 as a function of angle of attack for PRESS and ACES II. The drag coefficient for PRESS was calculated using SHABP as described previously. The drag coefficient for ACES II was obtained from wind-tunnel experiments.[13]

The minimum value of $C_dS$ for PRESS occurs at an angle of attack of approximately 40 deg, which is near the angle at which the acceleration exposure limit $A_w$ is a maximum, namely 35 deg. Thus, the dynamic pressure limit as given by Eq. (10) is maximum for an angle of attack between 35-40 deg as indicated by the solid curve of Fig. 9 for a 50th percentile pilot. Note that the dynamic pressure of ACES II does not have such a pronounced peak, because minimum $C_dS$ and maximum $A_w$ occur approximately 90 deg out of phase. The existence of the higher-allowable dynamic pressure limit for PRESS is the result of two factors: 1) tailoring the seat shape to have minimum aerodynamic drag with the pilot's spine perpendicular to the windstream, and 2) the larger mass of PRESS.

PRESS' aerodynamic shape is trimmed to zero pitching moment at approximately 50 deg, as described previously. One of the goals of this work was to design an ejection seat capable of operating safely up to dynamic pressure of 2000 psf. The PRESS seat attains this goal for a range of angles of attack from 19-57 deg, as shown in Fig. 9 at the moderate injury risk level. Thus, it is possible to exceed the stated goal of $q = 2000$ psf at the trim condition of 50 deg. The design concept includes an active pitch control system to reduce the time for the seat to rotate from the orientation prior to ejection to trimmed attitude. Achieving the trimmed condition quickly with minimal overshoot is also an important consideration is designing the control system that is discussed in the next section.

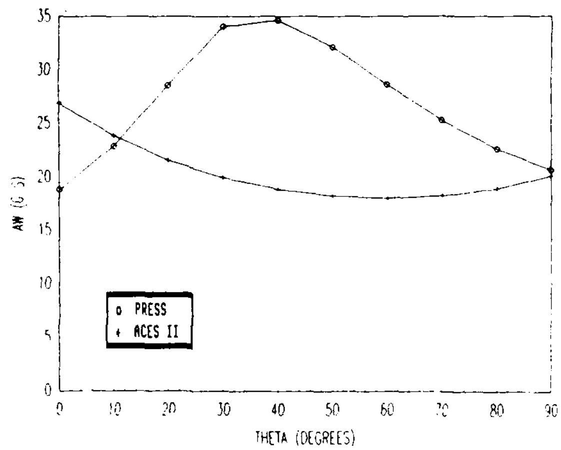



**Fig. 7 Acceleration limits ($A_w$) of PRESS and ACES II.**

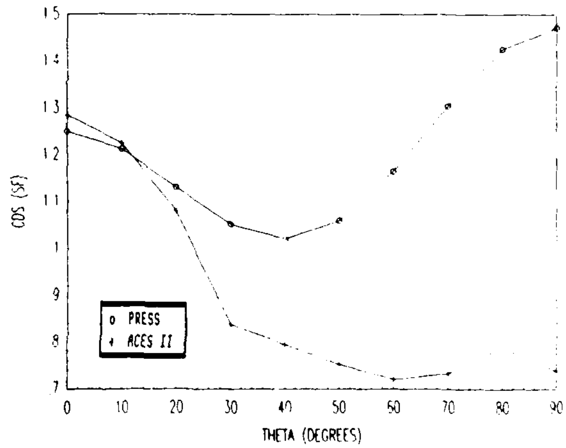



**Fig. 8 Drag comparison of PRESS and ACES II.**

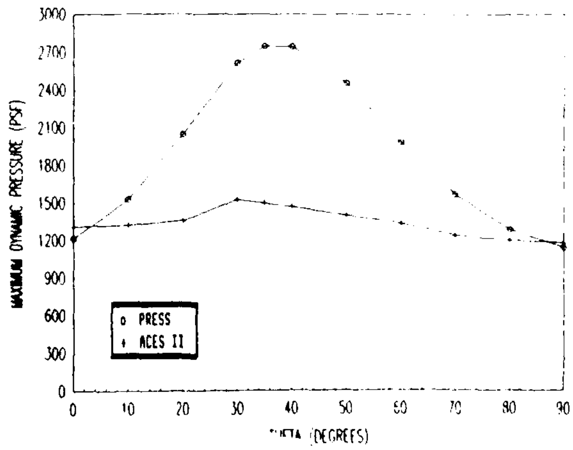
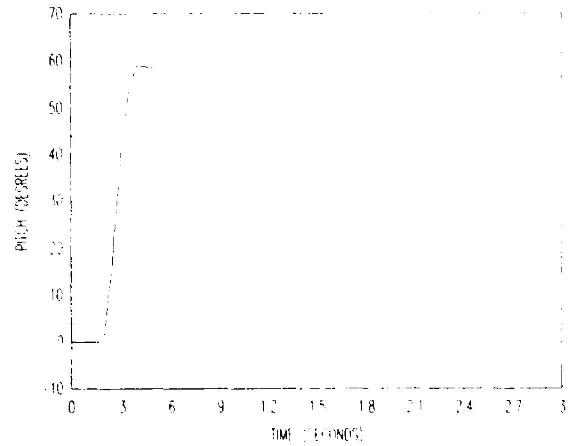
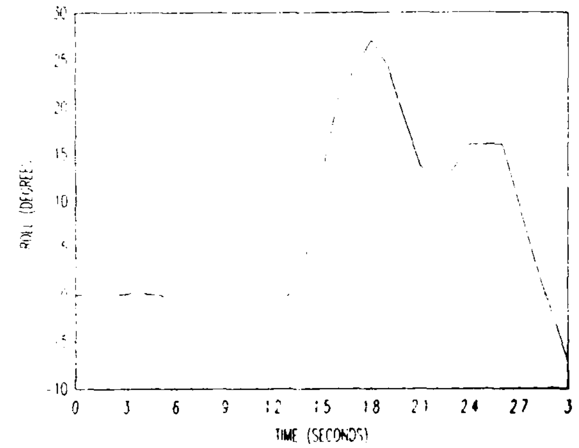


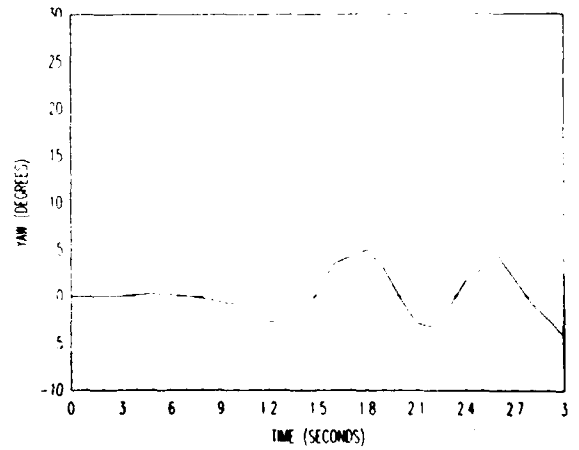

**Fig. 9 Maximum dynamic pressure limits at a moderate probability of injury for the PRESS and ACES II seats.**



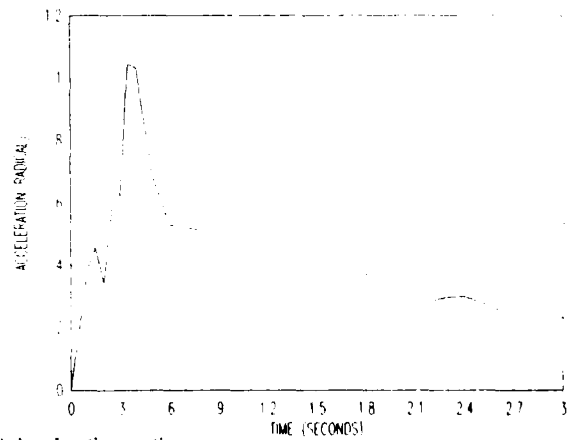

a) Pitch vs time



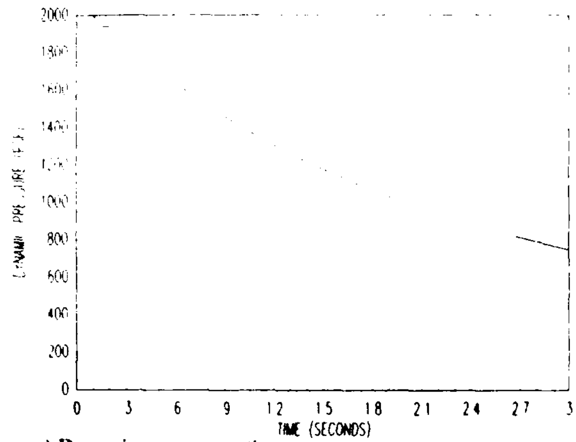

b) Roll vs time




c) Yaw vs time




d) Acceleration vs time




e) Dynamic pressure vs time

**Fig. 10 Results of a 2000 psf ejection of PRESS.**

With refinement to the aerodynamic shape so that pitch trim and minimum drag both occur at the angle of attack corresponding to deceleration perpendicular to the spine, Fig. 9 shows it would be possible to achieve dynamic pressure limits in excess of 2500 psf at the moderate injury risk level.

A second advantage of the PRESS seat with respect to the ACES II seat is that the PRESS seat experiences these higher dynamic pressures with the added benefit of a cowling for windblast protection. The ACES II provides no such protection, and so the pilot experiences the full brunt of the windblast. Note that the injury risk level presented in Fig. 9 does not include the injuries due to windblast burns and flailing (see Disselkoen et al. for further discussion).[1]

## Simulation and Control

PRESS ejections were simulated by computation techniques to substantiate PRESS' characteristics. The simulation was accomplished using the EASIEST program, which was developed by the Boeing Aircraft Company.[14] The simulation was run from catapult initiation to stabilization in the windstream to observe PRESS' dynamic characteristics and the g-forces exerted on the pilot. An important assumption required to run the simulation, and also a significant limitation, is that the seat and man are a rigid-body combination with a constant center of gravity.

The stability analysis demonstrated that the PRESS seat with a 50th percentile pilot should achieve a stable pitch attitude with a trim angle of attack of approximately 50 deg. Initial simulations showed that the seat rotated to the pitch trim angle but tumbled around the pitch axis, indicative that there was not enough aerodynamic damping to stop the seat at its predicted stability point. The seat needed a control system to orient it to the pitch attitude of the stable point. Furthermore, the control system would have to eliminate almost all of the seat's angular momentum because of low aerodynamic damping. Control was not required in roll and yaw because there are no large aerodynamic moments present in these axes.

An adaptive pitch (angle of attack) pitch-rate feedback controller was required as described by Disselkoen et al.[1] The system controls a variable-pitch vectorized nozzle with the angle and rate inputs. An adaptive gain was used to control the large amplitude difference between slow and high-speed aerodynamic moments. The control system turns off when the control rocket expires approximately 0.5 s after ejection initiation.

The results of the simulation (see Fig. 10) show an ejection at a dynamic pressure of 2000 psf (Mach 3 and 44,000 ft). The

pitch plot demonstrates that the control system directed the seat to 50-deg angle of attack, and after the control system turned off the seat remained stable within $\pm 3$ deg. Also, the roll and yaw plots show that the seat does not deviate significantly in these axes. Note that at 2.2 s, the seat has decelerated to a safe drogue shoot deployment level (950 psf).[4] The corresponding acceleration radical [see Eq. (3)] is also shown in Fig. 10 for a moderate probability of injury. As had been predicted, it is near one inicating only a moderate probability of injury. Note that this agreement substantiates the assumption stated earlier that the static accelerative forces approximate the dynamic response.

## Conclusions

The biomechanic and aerodynamic analyses indicate the PRESS has very beneficial $g$-tolerance and ejection characteristics. The PRESS seat significantly increases pilot $g$-tolerance over a reclined seat with an equal seat-back angle. For ejection, the PRESS seat provides aerodynamic stability at an angle of attack that greatly enhances the pilot's ability to tolerate decelerative forces. This enhancement along with high-speed windblast protection provided by the cowling gives PRESS safe ejection capability at dynamic pressures up to 2000 psf. Overall, PRESS has significant advantages over conventional ejection seats, which could be exploited in a future advanced fighter aircraft.

Studies are currently being done or planned in some aspects of pronated fighter seats such as centrifuge testing of the forward leaning position and aerodynamic analyses. A study currently underway at the Air Force Institute of Technology includes low-speed water-tunnel and wind-tunnel testing of PRESS.

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